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Performance of Steel Plate Girders with Inclined Stiffeners

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ABSTRACT

Slender webs in steel plate girders are prone to local and shear buckling at relatively low shear and thus, need be stiffened to increase the strength and stability of the girders. The conventional way is to provide vertical stiffeners at specified intervals, but this practice serves only to prevent the buckling of web. Provision of inclined stiffeners, in addition to improving buckling resistance, forms a truss-like girder which allows those stiffeners to carry some percentages of forces exerted in the girder. This paper, therefore, presents the ultimate performance of thin-webbed plate girders containing inclined stiffeners. Five simply supported plate girders of practical size were tested to failure under concentrated load applied at the mid-span. This study focuses on the effects of different inclination angles of intermediate stiffeners, θ on the load carrying capacity and post-buckling behaviour. Five different inclination angles, viz., 90°, 75°, 60°, 45° and 30°, measured from the bottom flange, were accounted for in the test series. Considerable variations of strength, failure characteristic and load-deflection response can be observed due to effects of such inclinations. Test results have shown significant increases in the ultimate strength from 11% to the extent of 50% as the angle of inclined stiffeners reduced. All the girders exhibited shear-dominated behaviour in the web panels at failure.

Keywords: Slender plate girder; inclined stiffener; load carrying capacity; post-buckling behaviour

INTRODUCTION

Use of fabricated plate girders is common in industrial buildings or highway bridges when large standard rolled sections are still inadequate to carry high in-plane bending and shearing forces over long span. Typical thin-webbed plate girders are stiffened transversely at certain intervals, subdividing the web plate into several panels to provide overall structural stability upon early web elastic buckling in shear. In addition to preventing flange twisting problem, provision of intermediate stiffeners serves as boundaries for the development of tension field in web panels. Post-buckling behaviour of thin webs was first noticed in the early 1930s for thin, membrane-like structures used in aircraft constructions (Wagner 1931). From then on, the theory of diagonal tension started gaining importance further. The design philosophy of vertically stiffened plate girders of the proportions used in civil engineering has gone through major changes as a result of massive research efforts during the past decades (Basler 1961; Porter et al. 1975; Herzog 1989; Lee et al. 1996; Shanmugam and Min 2007; Yatim and Shanmugam 2015; Azmi et al. 2017; Reis et al. 2019; Shao et al. 2020).

Stability of plate girder webs may also be enhanced by subdividing the individual panels with horizontal stiffeners. Numerous studies were carried out in the past to investigate the effects of horizontal stiffeners in web panels on the ultimate performance of the girders (Ostapenko and Chern 1971; Horne and Grayson 1983; Graciano 2005; Alinia and Moosavi 2009; Chacon et al. 2019). Other related works contributing to the knowledge of thin-webbed plate girders may be found elsewhere (Basler and Thurlimann 1961; Lee and Yoo 1998; Shanmugam et al. 2003; Yatim et al. 2011; Xiao et al. 2019; Al-Azzawi 2020). The conventional vertical stiffeners, except those at load points, do not carry any load and serve only to prevent the web from buckling. By placing the intermediate stiffeners diagonally across each panel, a trussed girder is formed and the stiffeners are thereby carrying a portion of the load in addition to performing in an efficient manner their given tasks of preventing buckling (Jensen and Antoni 1941). Inclined stiffeners would also have the advantage of limiting the shear factor without requiring additional longitudinal stiffeners (Guarnieri 1985). Nevertheless, installation of inclined stiffeners may cause uneven shapes and unequal subdivisions of web panels at the top compression and bottom tension flanges, thus resulting in a complicated analysis due to the complex behaviour of such panels at buckling.

Other web stiffening techniques such as externally bonded polymers are too expensive that the construction is becoming impractical. The need to consider inclined stiffeners should not be over-looked and that their potential contribution to the stability of thin webs seems to require more attention. Variations of ultimate load behaviour resulting from the inclination angle of stiffeners need be examined through physical observations in order to obtain clear pictures of the elastic and inelastic responses under loading. The available information in the literature may not be sufficient to comprehensively understand the behaviour of plate girders containing inclined stiffeners.

A series of tests on plate girders having different angles of inclined stiffeners has, therefore, been conducted. The plate girder webs were made slender and hence susceptible to buckling even at a low amount of shear. Attention was focused on variations of load carrying capacity, load-deflection response and failure characteristics. Details of the experiment are described herein in detail. This paper will also demonstrate a definite increase in efficiency of plate girders in order to highlight the benefits of employing inclined stiffeners over the conventional vertical stiffeners.

EXPERIMENTAL PROGRAMME

DETAILS OF THE EXPERIMENTAL GIRDERS

Plate girders originally tested by Shanmugam and Baskar (2003) were redesigned to suit the available test facilities and the objectives of the present study. The design was carried out in such a way that the girder is predominantly under shear and failure due to lateral torsional buckling is prevented. Five plate girders were fabricated using mild steel plates of Grade 43A which is equivalent to Grade S275 and complying with code BS 4360: *Specification for weldable structural steels*. Flat plates of specified dimensions were measured, marked and machined accurately to size. All the components were welded together with continuous fillet welds using a low temperature welding system to reduce the distortion of the steel materials. As precautions, lateral supports were provided at certain intervals to prevent large initial imperfections of the thin web plate. All the stiffeners were welded accordingly on both sides of the web.

The basic configurations were kept the same in all the girder specimens in order to have a constant span length, L = 2200 mm, web thickness, t_w = 2 mm, web depth, d = 500 mm, flange width, b_f = 100 mm, flange thickness, t_f = 10 mm, web slenderness ratio, d/t_w = 250 and aspect ratio b/d = 1.04. Notation b refers to width of web measured across the centroid of the trapezoidal-shaped panel. All the girders differ from each other in term of the angle of inclination of the intermediate web stiffeners, θ which varies from 30° to 90° in the increments of 15°. They are identified in the text as PG–90, PG–75, PG–60, PG–45 and PG–30. Notations 90, 75, 60, 45 and 30 indicate θ in angular degree. Figure 1 shows the elevation and cross-sections of a typical experimental girder.

TEST SET-UP AND INSTRUMENTATION

The girders were placed in the self-straining test rig over the strong, simple supports at their end bearing stiffeners to avoid local failure of the lower flange and web. Sufficient care was taken to ensure the correct positioning of the girder such that the mid-point of the girder was in line with the centroid of the load cell. Measurement of deflection was made at selected points by using general purpose LVDT transducers connected to a data logger. The measurement enables real-time plotting of load-deflection responses at different stages of loading automatically through a computer. The LVDTs were mounted firmly on a rigid frame isolated from the test rig so as to ensure disturbance-free measurement of displacements. A typical test set-up is shown in Figure 2.

RESULTS AND DISCUSSION

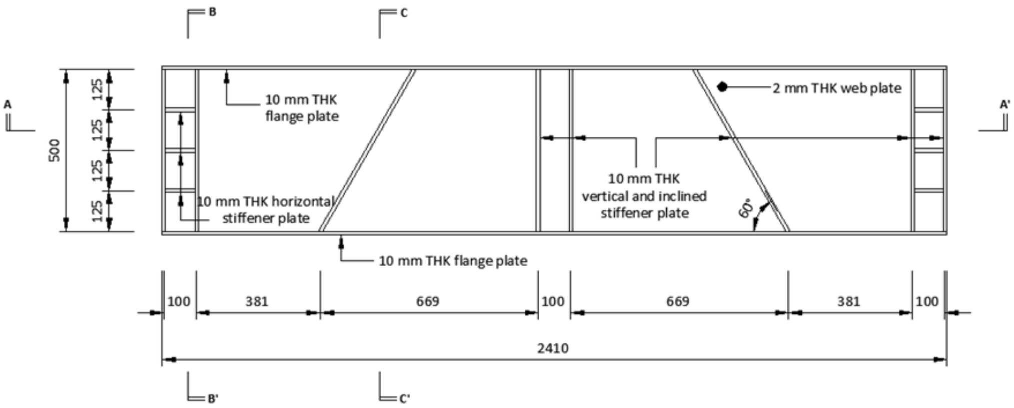
The girders were tested to the point of collapse under a central concentrated load applied at the mid-span. Results for ultimate loads, load-deflection relationships, deformation behaviour and failure characteristics obtained from the tests are reported herein.

ULTIMATE LOAD CAPACITY

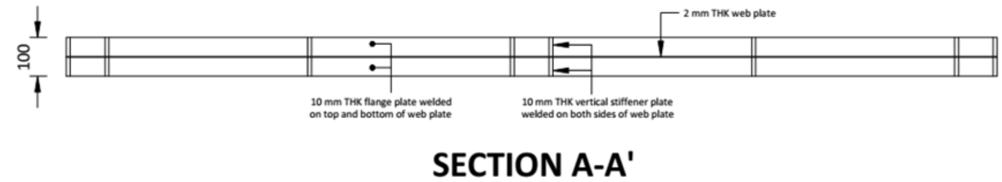
Table 1 lists the ultimate load capacity, P_u of the girders. The test girders were so designed that they could be used to assess the influence of inclined stiffeners on post-buckled web behaviour under constant shear. It is apparent from the test results that the ultimate load of the girder increased considerably to the extent of 50% when the inclination angle of stiffeners, θ reduced from 90° (i.e., PG–90) to 30° (i.e., PG–30). Also, an average increase of ultimate load by approximately 10% can be found from one girder to another when θ was reduced by 15°. These indicate the effectiveness of inclined stiffeners in carrying certain amounts of applied load through the distribution of forces as in truss with diagonal members, hence larger load can be sustained by the girders in excess of the maximum capacity attained by the conventional girders. In addition, the trapezoidal-shaped web panels resulting from the presence of inclined elements develops larger width of tension field that enabled the thin web to sustain higher tensile force exerted within the panels compared to the conventional rectangular ones.

LOAD – DEFLECTION RESPONSE

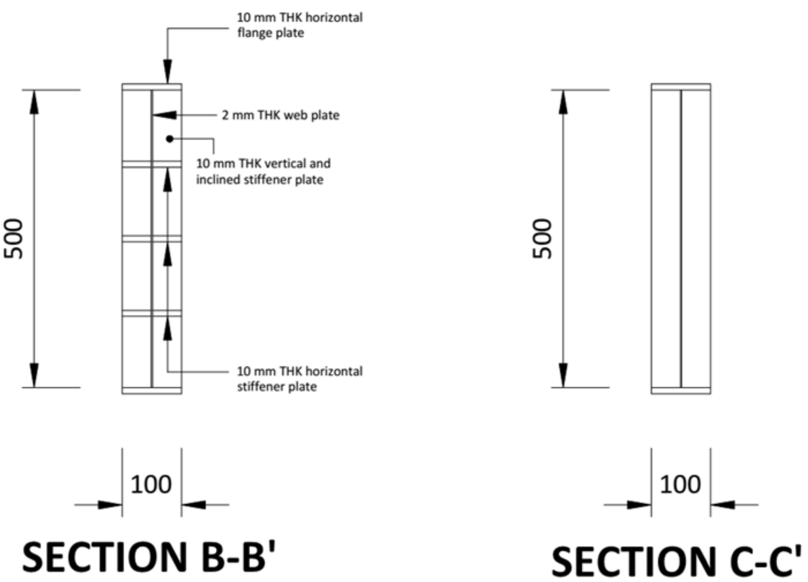
Figure 3 shows load-deflection plots of the girders for comparison purposes in order to highlight the response due to influence of inclined stiffeners. Gradual drop of applied load can be observed in all the girders after reaching the maximum capacity, indicating the yielding of web material. Evidently, girders with lower angle of inclined stiffeners show greater bending stiffness indicated by the slope of the curves within the elastic phase that delays the formation of buckling in the web panels to certain extents. This



(a)



(b)



(c)

FIGURE 1. Typical details of experimental girder

observation highly portrays the beneficial use of inclined plates as stiffening element for thin-webbed members in bending.

It appears that girders PG–90 and PG–75 show a drastic drop in the applied force after attaining the maximum capacity at a lower vertical deflection; but on the other hand, girder PG–30 failed at relatively larger deflection and exhibits ductile deformation feature from the beginning of plastic phase to stages beyond failure load. This could be attributed greatly to the fact that when θ is of lower value, wider tension band is developed within the web panels, thus allowing the girder to carry larger amount of tensile stresses induced in the thin plates. This in turn delays the yielding of web, hence the ultimate load capacity.

DEFORMATION AND COLLAPSE BEHAVIOUR

Concentrated load was applied steadily onto the top flange of the girders with constant rate. At the initial stages of loading, the girders underwent elastic bending without appreciable amount of vertical deflection especially at the mid-span. After attaining the critical buckling load, the panels started to buckle along the diagonal, indicating the

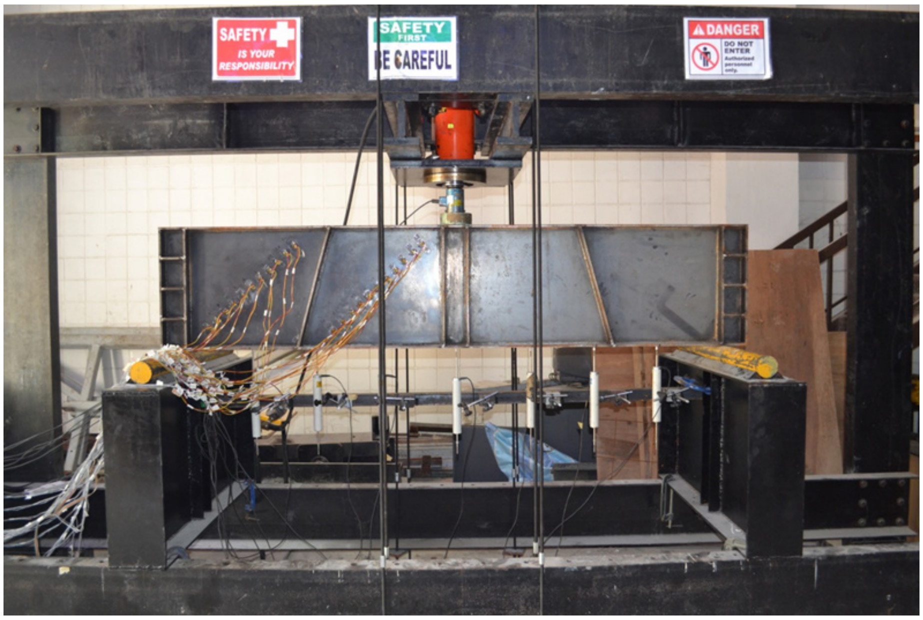


FIGURE 2. Typical test set-up

TABLE 1. Comparison of ultimate load capacities

Girder	Ultimate load, Pu (kN)
PG–90	219
PG–75	244
PG–60	262
PG–45	295
PG–30	328

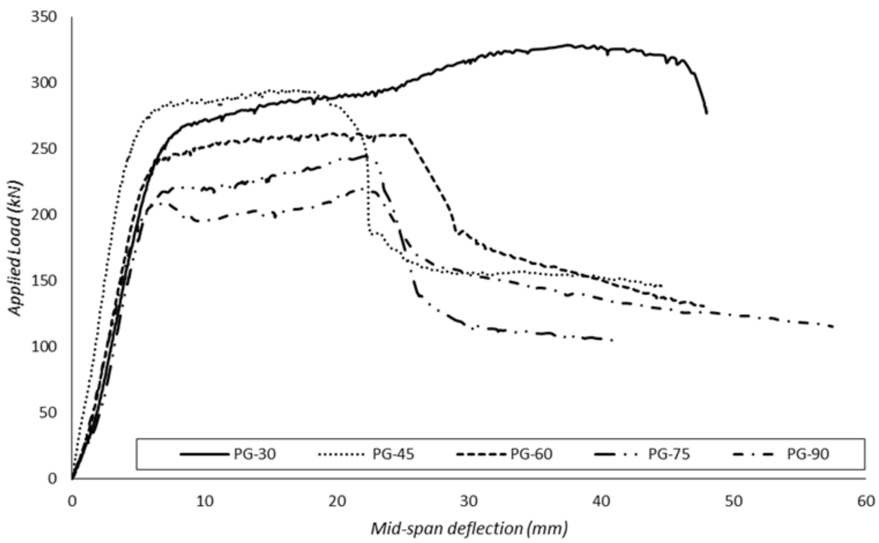


FIGURE 3. Comparison of load-deflection responses

formation of web tension field as presented in Figure 4 for a typical girder. Further application of compressive stress in post-buckling phase was resisted by tensile membrane action, leading to increase in out-of-plane deformation of web. At this stage, application of loading in any increment only resulted in dramatic increase of the corresponding vertical deflection, compared to that of the elastic phase. Such behaviour is indeed due to gradual loss in the girder's flexural stiffness.

The applied force began to drop gradually after reaching the ultimate point, indicating the yielding of web plate, hence loss of shear resistance in the girders. Beyond the maximum load, girders swayed to one side in most cases and deformation of webs was obvious, associated with plastic hinges in the top and bottom flanges as shown in Figure 5. These hinges were caused by the vertical component of the pulling force due to tension field mechanism. It appears from the figures that the lower the inclination angle of the intermediate stiffeners, the larger the angle of tension band formed in the web panels near to the point of load application. This occurred due to reduced dimension of web panel at the compression flange from which the tension field action anchored to. Overall, all the girders exhibit shear dominated failure.

FIGURE 4. Formation of diagonal buckling in typical web panels

(a)

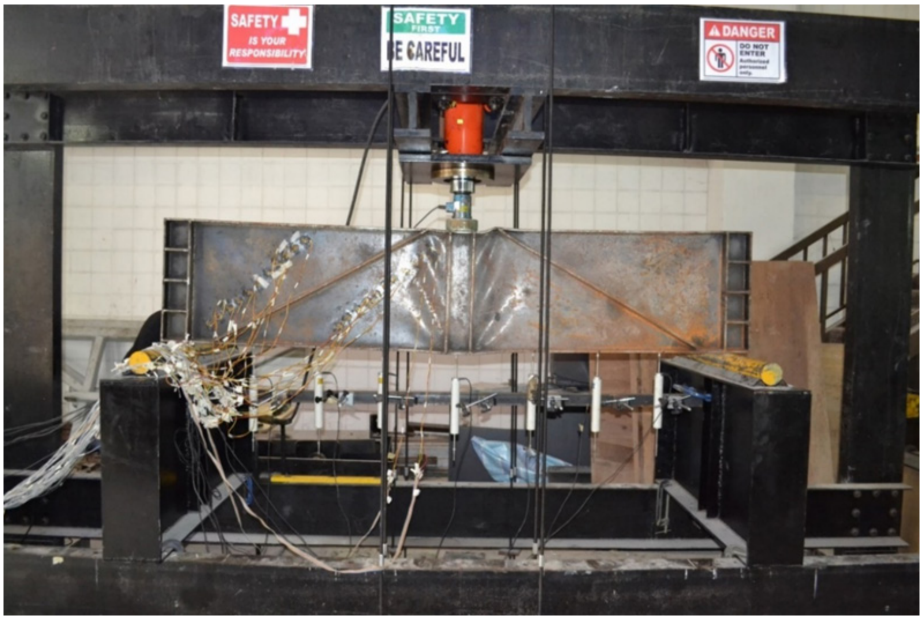

SAFETY
IS YOUR RESPONSIBILITY
SAFETY FIRST
DANGER
DO NOT ENTER

(b)


SAFETY
IS YOUR RESPONSIBILITY
SAFETY FIRST
DANGER
DO NOT ENTER

(c)

(d)



(e)

FIGURE 5. Deformation behaviour at failure (a) Girder PG–90, (b) Girder PG–75, (c) Girder PG–60, (d) Girder PG–45, (e) Girder PG–30

CONCLUSIONS

Five steel plate girders having different inclination angles of intermediate stiffeners were tested to failure under monotonic load applied at the centre of gravity of the sections. Results have shown considerably increase in the ultimate strength to the extent of 50% when the angles of stiffeners were reduced, indicating significant contribution of the inclined stiffeners in carrying some percentages of internal forces exerted to the web panels. The trapezoidal-shaped web panels result in larger width of web tension band, thus larger tension force can be carried in post-buckling phase compared to the conventional rectangular panels. Appreciable variations of bending stiffness may be observed in the load-deflection responses due to effects of inclination angle of the intermediate stiffeners. The curves also show a gradual drop in the applied force after attaining the ultimate point. Results for deformation characteristic are presented for all the girders. In many cases, the girders swayed to one side with tremendous buckling at the web and top flanges. Overall, this study has provided useful information and some insights in respect of the ultimate load behaviour of plate girders containing inclined stiffeners.

DECLARATION OF COMPETING INTEREST

None.

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